The Fusion Energy Revolution

Background, Science, Investment, and Hyperfusionization

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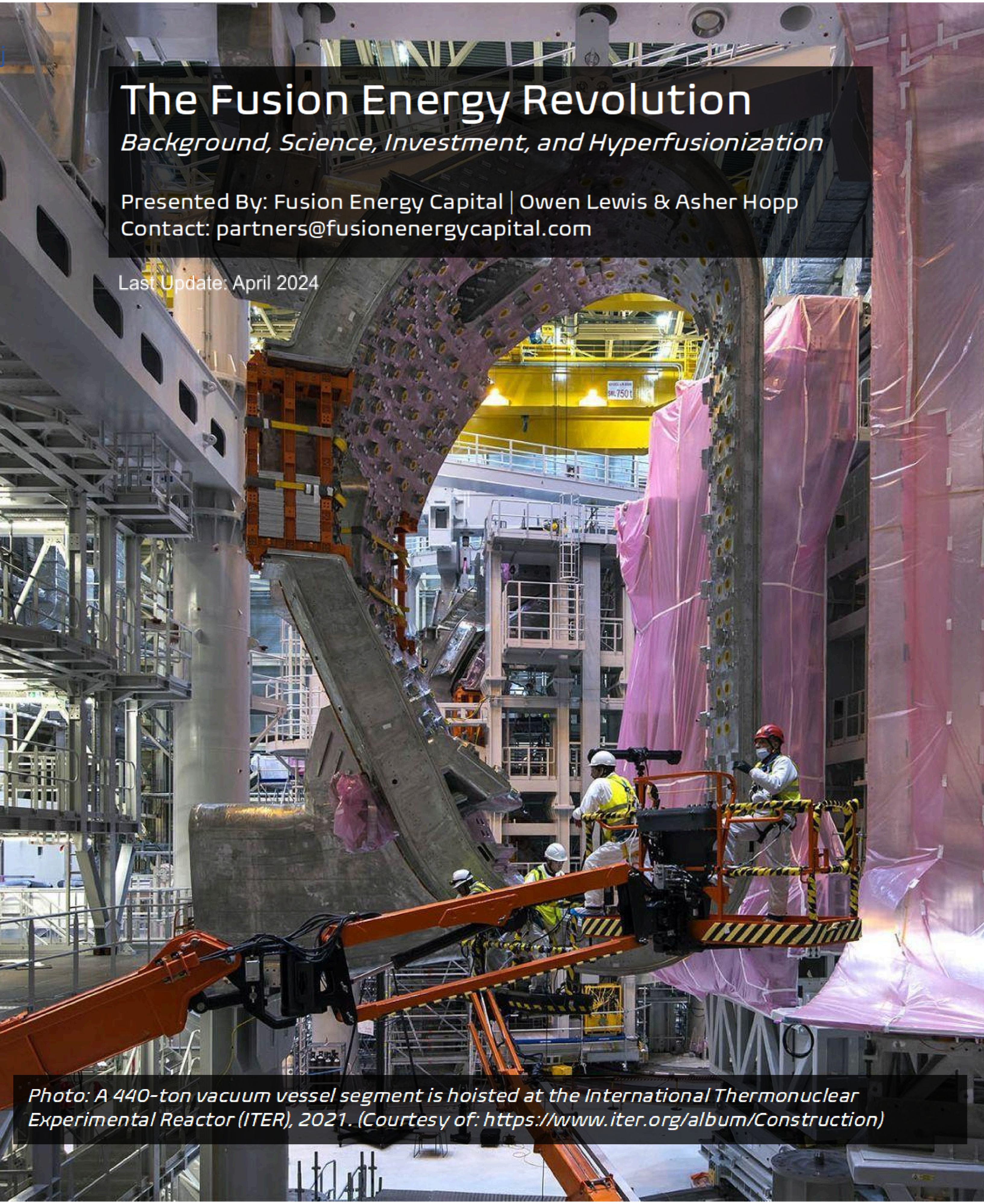

Photo: A 440-ton vacuum vessel segment is hoisted at the International Thermonuclear Experimental Reactor (ITER), 2021. (Courtesy of: https://www.iter.org/album/Construction)

"Fusion is too important for just one shot on goal.”
—Martin Greenwald

“I would like nuclear fusion to become a practical power source. It would provide an inexhaustible supply of energy, without pollution or global warming.”
—Stephen Hawking

“It’s probably the last energy source we’ll ever tame. I think of the trajectory from taming fire and it finally completes in fusion, because we’ll have tamed the energy source of the stars.”
—Dennis Whyte

“A star is drawing on some vast reservoir of energy by means unknown to us. This reservoir can scarcely be other than the subatomic energy which, it is known exists abundantly in all matter; we sometimes dream that Man will one day learn how to release it and use it for his service. The store is well nigh inexhaustible, if only it could be tapped.”
—Sir Arthur Eddington, 1920

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Introduction

What is **hyperfusionization**? Hyperfusionization is a word we coined to describe a future in which commercially available fusion energy infrastructure is the dominant source of grid energy. In a hyperfusionized world, fusion energy has displaced the combined market positions of biomass, coal, natural gas, solar, wind, hydroelectric, geothermal, and nuclear fission. In a hyperfusionized future there are no debates about carbon emissions, there is no geopolitical tension over fossil fuel resources, and there is abundant energy available for residential, commercial, and industrial users. Hyperfusionization is a realistic vision for the end of this century based on peer-reviewed science, business analytics, and macroeconomic conditions.

This paper lays out the case for private investment in fusion energy. We describe the fundamental context of energy in the lattice of human civilization, how the energy economy developed into what we have today, and the shortfalls of today's energy economy. We then review the underlying scientific merit of fusion energy research and development, and how commercialized fusion will become the dominant force in energy markets of the future. Finally, we address the business case for investing in fusion energy.

We believe that fusion energy is the next and final chapter in the 1-million-year history of our species' pursuit of energy. The last three centuries have seen enormous advancements in energy technology, several orders of magnitude more valuable than the previous iteration. Wood fire, biofuels, coal, steam, electricity, crude oil, natural gas, solar and wind energy, hydroelectric, geothermal, and energy from nuclear fission – each has been a monumental step forward in advancing the human condition driven by the brightest inventors among us, and fusion energy may yet outstrip them all in our lifetime.

There are innumerable investment strategies that investors must consider – fixed income bonds, securities and stocks, commodities, art, real estate, politics and influence. Each has unique advantages and disadvantages. We believe that fusion energy deserves a special allocation as an investment in *science* itself, one that, we will argue, has the potential for great financial return. If we are successful in commercializing fusion energy we will have a substantive impact on every geopolitical power, on every industry, and on any person who uses an electrical grid to improve their personal life or power their business.

Fusion energy offers the most promising path for achieving sustainable, clean, safe, high-output, reliable, and nearly unlimited energy with scientific consensus around its legitimacy. We hope you join us on this journey by learning about fusion energy and considering an investment to bring about a better world.

A Brief History of Energy

Energy can be defined as the ability to do work. When you have more energy, you can do more work. When you have less energy, you can do less work.

Chimpanzees, our forest cousins, have muscles and are able to consume high-calorie fruits to become masters of their forests. Neanderthals mastered and understood fire, which helped them develop cooking, create art, and invent tools. Modern humans have advanced to more efficient energy technologies. We have never had a wider variety of energy options. We have fossil fuels such as coal, oil, and natural gas. We have renewable energy such as solar photovoltaic, wind and hydro turbines, and geothermal vents. In the last century we developed nuclear fission – a process of generating high amounts of energy by splitting heavy atoms, like uranium.

There are many different types of energy including heat, light, and electricity[1]. Archaeologists have discovered prehistoric evidence of early protohumans using energy in the form of fire to improve their lives over 1 million years ago[2]. As far as we know, since that first fire was lit, humans have strove to find new and clever ways to create and use energy.

There was relatively slow progress in new forms of energy, from the mastery of fire, one million years ago, until the industrial revolution in the 18th century when coal was exploited to supercharge western civilization. In 1769 James Watt patented the first steam engine, kicking off the industrial revolution. Since the industrial revolution, countries and companies have competed with one another to create more energy with higher efficiency and less pollution. Thomas Edison built the first coal power plant in the late 19th century to power outdoor lamps.

When Albert Einstein announced his proof of mass-energy equivalence in 1905, scientists and engineers gained a new understanding with which to approach energy. Because mass and energy are connected by a constant, we can calculate the efficiency of any fuel and engine. Having this rubric to evaluate energy projects led to a century of advances that outpaced the previous 5,000 years of man's recorded history. In the first half of the 20th century we gained geothermal power and nuclear fission. In the latter half of the 20th century, solar panels and offshore wind were added to the energy mix. In the 21st century, due to new resource extraction and production techniques, there has been a tremendous increase in the use of liquified natural gas.

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[1] "What is energy? Forms of energy." U.S. Energy Information Administration. Dec 13, 2021. https://www.eia.gov/energyexplained/what-is-energy/forms-of-energy.php.

[2] "From the ashes, the oldest controlled fire." ScienceNews. Bruce Bower, April 2, 2012. https://www.sciencenews.org/article/ashes-oldest-controlled-fire.

People without significant energy security have fallen behind, and those with energy security have led the world in both innovation and quality of life. According to data collated by the World Bank, electricity use, access, reliability and cost competitiveness are all directly correlated with a country's GDP. To put it more simply, there are no low energy, rich countries[3].

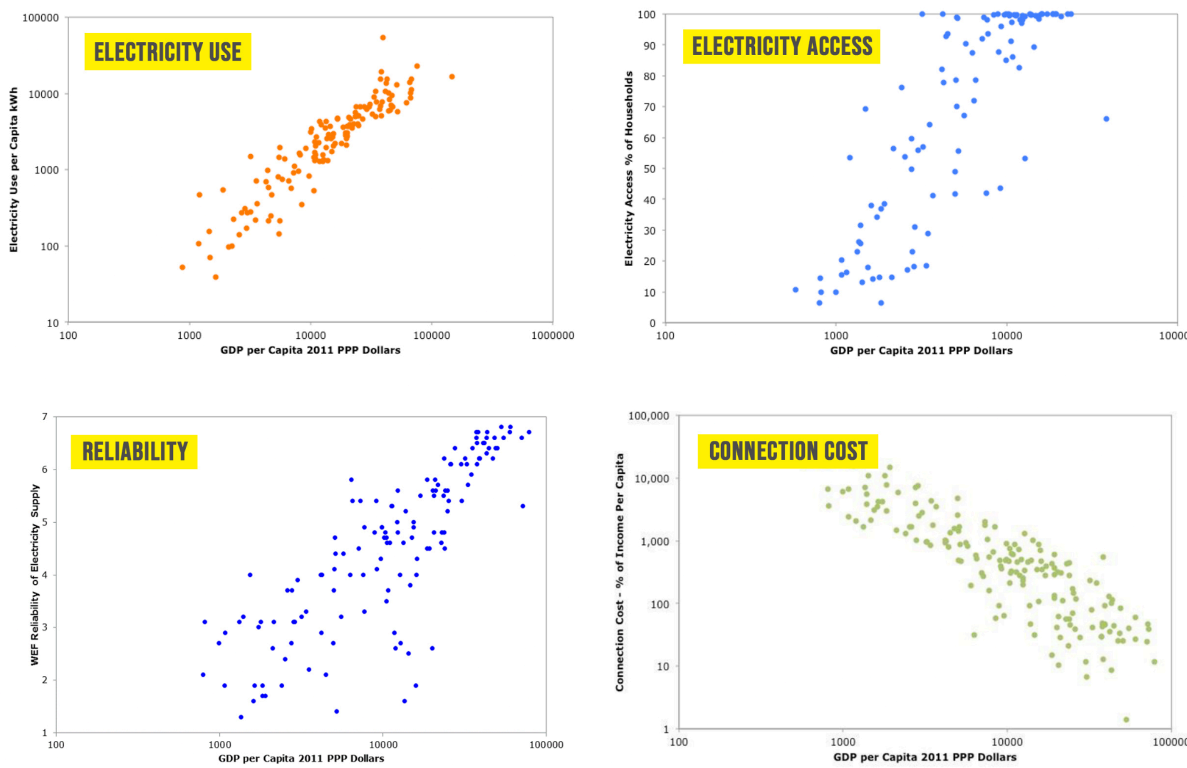


Figure 1: Dimensions of Energy and Per Capita Incomes. Source: World Bank[4]

Modern economies have developed complex electrical grids. One city may be a customer of several large centralized power plants, each with a different fuel or energy source. There are also decentralized energy assets on the grid including solar panels, wind turbines, and battery storage. The grid is composed of transmission lines and load balancers which deliver power to customers throughout the service area while taking in energy from all available sources. Energy grids are considered critical infrastructure and are protected as key elements of national security. We believe that fusion energy is the best way to ensure the continuation of a reliable grid, as well as access to abundant energy.

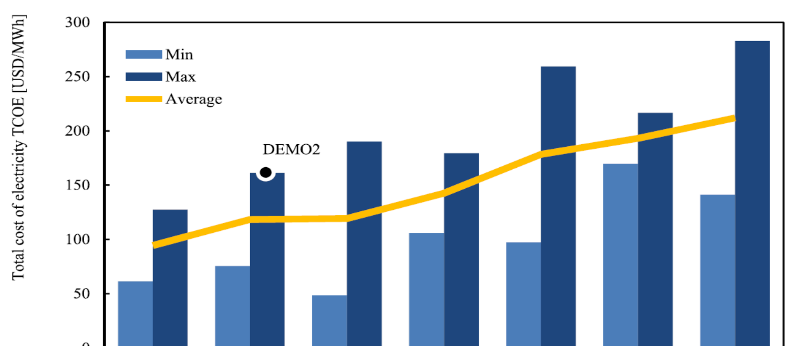
[3] "There are no low energy, rich countries." World Development Indicators. Todd Moss, Nov 5, 2019. https://www.weforum.org/agenda/2019/11/energy-poverty-africa-sdg7/

[4] "How much do we know about the development impacts of energy infrastructure?." The World Bank. Kelsey Jack, Mar 29, 2022. https://blogs.worldbank.org/sites/default/files/2022-03/microsoftteams-image.png.

Fossil Fuels, Renewables, and Fission Fall Short. Fusion is the Solution

Today's world uses a wide variety of energy sources. These can be split into three main types: Fossil fuels, renewables, and nuclear (fission), with fossil fuels making up a bit over 80% of the total.[5] Each has significant disadvantages compared to fusion. Fusion has all the benefits of both traditional baseload energy sources and renewables, with very few of the drawbacks.

Levelized Cost of Energy (LCOE) is the most commonly used metric to compare different energy sources. It looks at the cost of building and operating a power plant, divided by the value of the energy produced. Alone however, it's inadequate. To get the clearest picture, a second set of factors must be considered—referred to as externalities. These externalities are any costs the LCOE doesn't capture. These range from the effects of air pollution on human health, to the effects of climate change, land use, material use, reliability, capacity factor, waste and byproduct management, recyclability, dispatchability, transportability, storability, scalability, any need for long distance transmission lines, accidents, overcapacity, back-up base load costs, and any added cost of these things to the grid. Fusion compares very favorably to other energy sources on most externalities.



	Nuclear	Fusion	Wind onshore	Natural gas	Solar large PV	Coal	Wind offshore
Min	61	76	49	106	97	170	141
Max	127	161	190	179	259	217	283
Average	94	118	119	143	178	193	212

A good way to capture these external costs is with the Total Cost of Energy/Electricity, which is LCOE + externalities, though it's admittedly difficult to properly account for all external costs. Note that Figure 1 uses an expensive successor to ITER[6] when estimating fusion energy costs; any fusion power plant commercialized by a private company will cost significantly less.[7]

Figure 1: Total cost of electricity including external costs (TCOE). Source: Entler et al, 2018.[8]

Two of the most commonly recognized external costs are threats to human health from air pollution and accidents, and greenhouse gas emissions resulting in climate change. When different energy sources are compared, nuclear fission, wind, and solar come out on top, with nuclear having the best (lowest) combined risk to human health and greenhouse gas emission. Though fusion can't be compared yet, the value for current nuclear energy can be used as a good proxy. If anything, fusion will be even safer.[9]

[5] "Energy consumption by source, World." Our World in Data. https://ourworldindata.org/grapher/energy-consumption-by-source-and-region.
[6] "What Is ITER?" ITER. https://www.iter.org/.
[7] "The chase for fusion energy." Nature. Philip Ball, Nov 17, 2021. https://www.nature.com/immersive/d41586-021-03401-w/index.html.
[8] Entler et al. 2018. Approximation of the economy of fusion energy. Energy, Volume 152, pages 489-497. https://doi.org/10.1016/j.energy.2018.03.130.
[9] "The safest and cleanest types of energy by source." Our World in Data. Hannah Ritchie, Feb 10, 2020. https://ourworldindata.org/safest-sources-of-energy.

Another important way of comparing energy sources is Energy Return On Investment (EROI). This ratio describes the amount of usable energy produced from a given source relative to the energy used obtaining it. Modern industrial civilization needs a EROI of about 7 or higher to be viable.[10] The ideal type of energy will have a high EROI, meaning you get a lot of surplus energy out for a small amount of energy input. Existing nuclear power has the highest EROI, and fusion energy will be at least that high. When comparing EROI, it's important to note that it can be broken down into buffered (storage included), and unbuffered (storage not included), as Figure 2 illustrates. Renewables perform poorly compared to reliable energy sources like natural gas, hydro, coal, and nuclear fission, and will perform even more poorly compared to fusion.

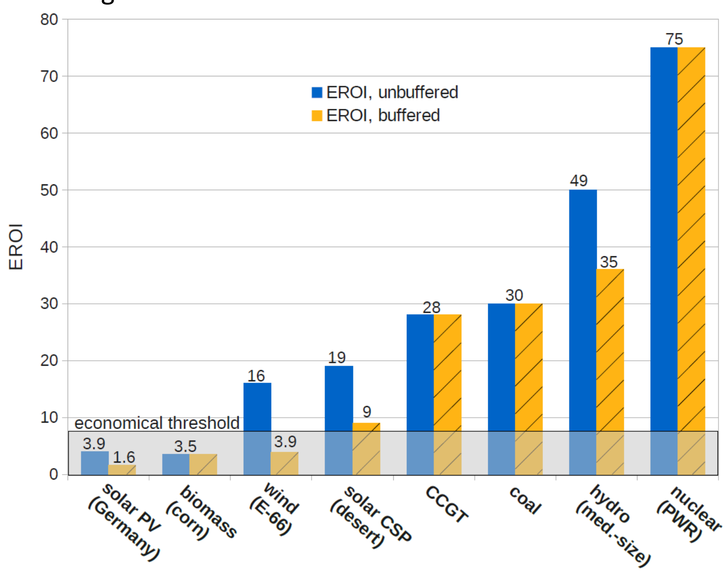


Figure 2: EROI of different energy sources (economic threshold is 7). Source: D. Weißbach et al, 2013.[11]

Fossil Fuels: Coal, Oil, and Gas

When it comes to fossil fuels, the shortcomings aren't exactly secret. Pollution is the main concern, both in terms of greenhouse gas emissions and particulates that harm human health. Climate change gets a lot of press, so we won't go into it here; but to put the health impacts in perspective, at least 1 million people a year may be dying as a result of particulates generated from burning fossil fuels, and possibly far more.[12,13] Developing an energy source like fusion that avoids the pollution problems of fossil fuels is not only important for human health and environmental concerns, but represents an unprecedented economic opportunity.

Renewables

Solar and Wind

Despite generally positive press, solar and wind energy have significant downsides—particularly their tendency to make electricity more expensive. While this may seem counterintuitive given the often low

[10] "EROI -- A Tool To Predict The Best Energy Mix." Forbes. James Conca, Feb 11, 2015. EROI -- A Tool To Predict The Best Energy Mix (forbes.com).
[11] Weißbach, D. et al. 2013. Energy intensities, EROIs, and energy payback times of electricity generating power plants. Energy, Volume 52, Pages 210-221. https://doi.org/10.1016/j.energy.2013.01.029.
[12] "Fossil fuel combustion kills more than 1 million people every year, study says." Ars Technica. Tim De Chant, Dec 16, 2021. https://arstechnica.com/science/2021/12/fossil-fuel-combustion-kills-more-than-1-million-people-every-year-study-says/#:~:text=Burning%20fossil%20fuels%20kills%20more,5.
[13] Vohra, K. et al. 2018. Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. Environmental Research. Volume 195. 110754. https://doi.org/10.1016/j.envres.2021.110754.

cost of electricity generated from solar and wind, their unreliable nature means they aren't dispatchable, which makes the electrical grid more costly, increasing prices.[14] The problem is that solar and wind production drop to zero when the Sun isn't shining or the wind stops blowing, necessitating complete backup from other sources. Compounding this is that peak generation often doesn't correspond to peak demand. For example, solar produces best during the middle of the day when the Sun is highest in the sky, but demand peaks in the morning and evening. When this overproduction occurs, solar power plants either have to reduce the amount of electricity sent into the grid, production from other types of power plants must be shut down, or the grid must be extended into other regions so the electricity can be sold elsewhere. All of these choices add complexity and cost.

Solar and wind farms are often built away from large population centers, increasing transmission costs significantly. There are also problems and expenses associated with lack of effective storage, the low energy density of solar panels and wind turbines, displacement of baseload sources, low electricity generation versus capacity, large land and materials use footprints compared to fossil fuels or nuclear fission, difficulties with recycling, and in the case of solar, the use of slave labor (Uyghurs in China) in global supply chains. Together these create significant environmental and societal costs, contribute to their overall unreliability, and increase electricity prices while decreasing grid robustness.

Geothermal

Geothermal relies on generating electricity from the internal heat of our planet. Rock deep underground is always hot, allowing electricity production around the clock. Because of this reliability, geothermal would appear to potentially be a major renewable energy contributor. While it works well in certain places,[15] the areas for new development are severely limited by geography and geology. There is an adaptation known as ultra-deep geothermal which proposes to utilize incredibly deep wells (~3–20 km) to generate electricity anywhere in the world, but this is very difficult technically, and has yet to be developed successfully. The current record holder for deepest well was 12 km, and it took two decades to drill.[16]

Biofuels and Biomass

Biofuels are considered to be carbon neutral because the carbon dioxide produced by burning them will soon be taken up by new plants. In practice, additional greenhouse gasses are emitted due to fossil fuel use during growing and production, nitrous oxide emissions from fertilizer use (1kg nitrous oxide is equivalent to 298 kg CO_2), and emissions from land use changes. Together these additions may make biofuel emissions higher than from burning fossil fuels.[17] Biofuels made from crops—as the majority of them are—also compete for farmland with food, resulting in higher local and global food prices, something poorer countries can ill afford. Many large environmental groups are cautious about or even

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[14] Greenstone and Nath. 2019. Do Renewable Portfolio Standards Deliver Cost-Effective Carbon Abatement? University of Chicago, Becker Friedman Institute for Economics Working Paper No. 2019-62. http://dx.doi.org/10.2139/ssrn.3374942

[15] "Ranking of largest geothermal plants worldwide as of January 2021." Statista. https://www.statista.com/statistics/525206/geothermal-complexes-worldwide-by-size/#:~:text=The%20largest%20geothermal%20plant%20in,spans%20over%2030%20square%20miles.

[16] "During the Cold War, the US and Soviets both created ambitious projects to drill deeper than ever before." BBC, Mark Piesing, 6th May 2019. https://www.bbc.com/future/article/20190503-the-deepest-hole-we-have-ever-dug.

[17] DeCicco et al. 2016. Carbon balance effects of U.S. biofuel production and use. Climate Change, 138, 667–680. https://doi.org/10.1007/s10584-016-1764-4.

oppose biofuels, though the governments of the U.S. and many other countries generally support them.[18,19] Biomass usually means burning wood pellets, often made by cutting down trees for that purpose. Surprisingly, around 60% of the European Union's renewable energy is from wood pellets, sourced by cutting down over a million acres of forest, primarily in the United States.[20] This does nothing to reduce CO_2 emissions over timeframes of less than a century, and contributes to biodiversity loss and habitat destruction.[21]

Hydro

Hydroelectric energy is generally able to provide reliable, baseload electricity through the continuous flow of water. Though this can change depending on the time of year or during droughts. A significant problem for hydro is that most of the best spots have already been developed, leaving little scope for expanding global capacity. Many of the remaining areas are in tropical countries with higher biodiversity. As hydro is quite environmentally damaging, vigorous debates on further development are ongoing.[22]

Nuclear Fission

In many ways nuclear fission should have been the perfect energy source: reliable, no emissions, energy dense fuel, and relatively small environmental footprint. Unfortunately, there are significant drawbacks; most well known are the problems of safety (Chernobyl, Fukushima), and what to do with long-lived, highly radioactive waste. Arguably these are manageable problems. Even when including these accidents, the safety of nuclear fission power plants is extremely high. A lot of nuclear waste can be recycled and reused as fuel, as is often the case in parts of Europe, making the issue much smaller than it appears. But perception is often king, and decades of concerted and vocal opposition have made new nuclear power plants very difficult to build, especially in Western countries—a trend that's unlikely to change soon. Even in the case of advanced Small Modular Reactors (SMRs)[23], which will be smaller, cheaper, and safer than conventional nuclear power plants, the problem of resistance and hostility remains. There are also geopolitical issues with the risk of even low enriched uranium getting into the hands of unfriendly or unstable regimes, and the perception that nuclear power plants could be used by these bad actors to produce weapons.

Fusion Energy is Clean, Unlimited, Safe, High-Output, and Politically Neutral

Fission versus Fusion

Fission and fusion are both nuclear processes—which occur in the nuclei (center) of atoms. Both convert mass into energy, as described by Einstein's famous equation: $E=mc^2$. Fission takes a big atom, like uranium, and releases large amounts of energy by splitting it into smaller pieces. Fusion does the

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[18] Selin, N. Eckley, and Lehman, Clarence. "biofuel." Encyclopedia Britannica, September 15, 2021. https://www.britannica.com/technology/biofuel.

[19] "Biofuels." IEA. https://www.iea.org/reports/renewables-2021/biofuels?mode=transport&region=World&publication=2021&flow=Consumption&product=Ethanol.

[20] "Europe Rethinks Its Reliance on Burning Wood for Electricity." NYT, Lois Parshley, May 17, 2022. https://www.nytimes.com/2022/05/17/climate/eu-burning-wood-electricity.html.

[21] "Letter Regarding Use of Forests for Bioenergy." Woodwell Climate Research Center. Feb 11, 2021. https://www.woodwellclimate.org/letter-regarding-use-of-forests-for-bioenergy/.

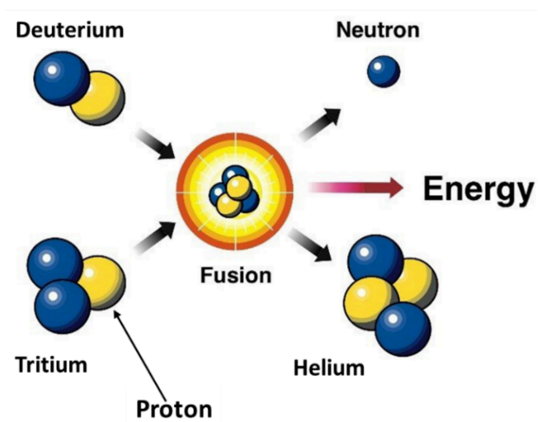
[22] Moral et al. 2018. Sustainable hydropower in the 21st century. PNAS, 115 (47) 11891-11898. https://doi.org/10.1073/pnas.1809426115.

[23] "Advanced Small Modular Reactors (SMRs)." Office of Nuclear Energy. https://www.energy.gov/ne/advanced-small-modular-reactors-smrs.

opposite, taking two smaller atoms, like hydrogen, and fusing them together into a larger one like helium, releasing enormous energy—around 3-4x that of fission.

How does Fusion work?

The Sun fuses hydrogen into helium by starting off with four protons, and through a series of steps converts about 0.7% of their mass into energy; with the end result being helium and a lot of energy. On Earth, this process is too hard; the reactions do not happen frequently enough at reasonable temperatures in small enough containers to be practical. The Sun gets away with it because its massive size lets it use gravity to create fusion conditions in its core—an impossibility on Earth. Instead, we tilt the odds in our favor a little by using heavier forms of hydrogen: deuterium (proton + neutron), and tritium (proton + 2 neutrons). This D-T fuel is considered the easiest to work with because it fuses at relatively low temperature, around 150 million degrees K, *only* about 10 times hotter than our Sun's core. Deuterium is abundant, and can be simply extracted from seawater. Tritium is trickier, as it is mildly radioactive with a short half-life of just 12.3 years; and doesn't really exist naturally. It can, however, be *bred* (created) from fusion produced neutrons interacting with a lithium blanket surrounding a fusion reactor core. There is significant work being done to figure out the best way to do this. Currently most tritium comes from existing nuclear fission plants, particularly CANDU reactors.[24]



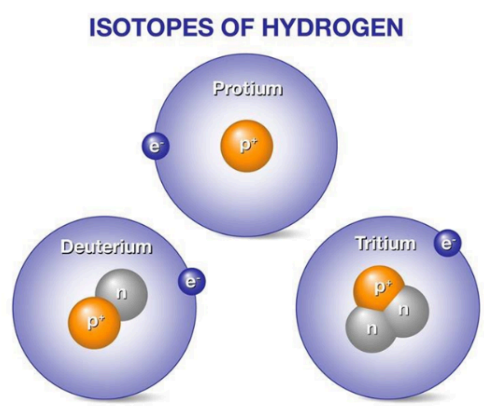


Figure 3 (Left): Tritium-Deuterium fusion. Image Credit: U.S. Department of Energy, via SciTechDaily.[25] Edited by Owen Lewis. **Figure 4 (Right):** Isotopes of hydrogen. Image Credit: General Atomics via the U.S. Office of Science.[26]

Reaction Temperatures and Fusion Fuels

The majority of private companies and big government projects tend to favor D-T, but some go other routes, including D-He3, D-D, and p-B11 fuels[27], though they require higher temperatures. The main advantage of these different approaches is fewer neutrons emitted, which means less radioactivity,

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[24] Pearson, R; Antoniazzi, A; and Nuttalla, W. 2018. Fusion Energy and Design. Volume 136, Part B, Pages 1140-1148. https://doi.org/10.1016/j.fusengdes.2018.04.090.
[25] Image Credit: U.S. Department of Energy, via SciTechDaily. https://scitechdaily.com/science-made-simple-what-are-nuclear-fusion-reactions/. Modified by Owen Lewis.
[26] Image Credit: General Atomics via the U.S. Office of Science. https://www.energy.gov/science/doe-explainsdeuterium-tritium-fusion-reactor-fuel.
[27] "Fuels." Wikipedia. Dec 14, 2022. https://en.wikipedia.org/wiki/Fusion_power#:~:text=Fuels%5Bedit%5D,side%20reactions%20can.%5B.

much less shielding, and ultimately a smaller, cheaper machine. These fuels can also allow direct generation of electricity, which permits savings in cost and size.

Fusion Machines

There are a variety of approaches being pursued when it comes to reactor design. Best known are the toroidal (donut-shaped) tokamaks (like ITER) and stellarators, which have historically received the most funding. Tokamaks and stellarators are examples of magnetic confinement fusion, which uses powerful magnets to confine and shape plasma, compressing it to fusion conditions. The other main approach to fusion is inertial confinement fusion, which often uses lasers to confine and compress fuel pellets to fusion conditions (e.g., the National Ignition Facility in the U.S.). Not all variations on this use lasers however; some fire projectiles into a capsule of fusion fuel, compressing it enough to fuse. A variety of other paths are also being pursued to achieve fusion, including magnetized target fusion, reverse field configuration, spherical tokamaks, the orbitron, z-pinch, and others.

Advantages of Fusion

Fusion is the *holy grail* of energy, having all of the pros of both traditional energy and renewables and very few of the cons. Not that fusion will be able to replace renewables overnight, or traditional energy sources either for that matter, but once commercialized we expect its use will expand rapidly. Some attributes of fusion include:

- Energy Dense: Fusion fuel contains over a million times more energy per kilogram than coal and natural gas, and at least 3-4x the energy of fission fuel like uranium.
- Sustainable, Abundant and Clean: Fusion will generate massive amounts of energy to power the next stage of human civilization with minimal impact on the environment. Fusion fuels used are generally abundant—essentially inexhaustible—and will allow energy production without CO_2, particulates, or other undesirable byproducts being emitted into the atmosphere. In other words, clean, abundant, reliable energy. Forever.
- Safe: Fusion will also be safe, with zero chance of explosion or meltdown. Because unlike nuclear fission, a fusion reaction will not just carry on by itself on Earth.
- Affordable: While the first few commercial pilot plants will be expensive, fusion could eventually be quite affordable. There are published papers describing fusion energy as being very cost competitive, potentially in the 40 – 50 $/MWh range[28,29], with some private companies estimating even lower prices. Even if costs are higher than this, it could help make the grid as a whole cheaper.
- Reliable: Reliability is vital to the smooth functioning of our grid, and ultimately our society. Fusion will provide *always on* power, reducing the need for expensive infrastructure investments like long distance transmission lines. Being weather-independent is a characteristic fusion will share with existing fossil fuel and nuclear power plants—a huge drawback for wind and solar. Fusion's capacity factor[30] will likely be high, 90% or more; similar to existing nuclear.
- Improving Living Standards: Fusion energy will also continue improving global standards of living and help reduce energy poverty. During the past few centuries, we've seen massive progress in

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[28] Scott, H; Woodruff, S; and Colleen, N. 2020. US Department of Energy (USDOE), Washington DC (United States). Advanced Research Projects Agency-Energy (ARPA-E). doi:10.2172/1820946.

[29] Hawker, N. 2017. 2020. A simplified economic model for inertial fusion. Phil. Trans. R. Soc. A378: 20200053.http://dx.doi.org/10.1098/rsta.2020.0053

[30] "What is Generation Capacity?" Office of Nuclear Energy. Mike Mueller, May 1, 2020. https://www.energy.gov/ne/articles/what-generation-capacity.

every standard of measure for human wellbeing. All of this ultimately hinges on abundant and reliable energy.

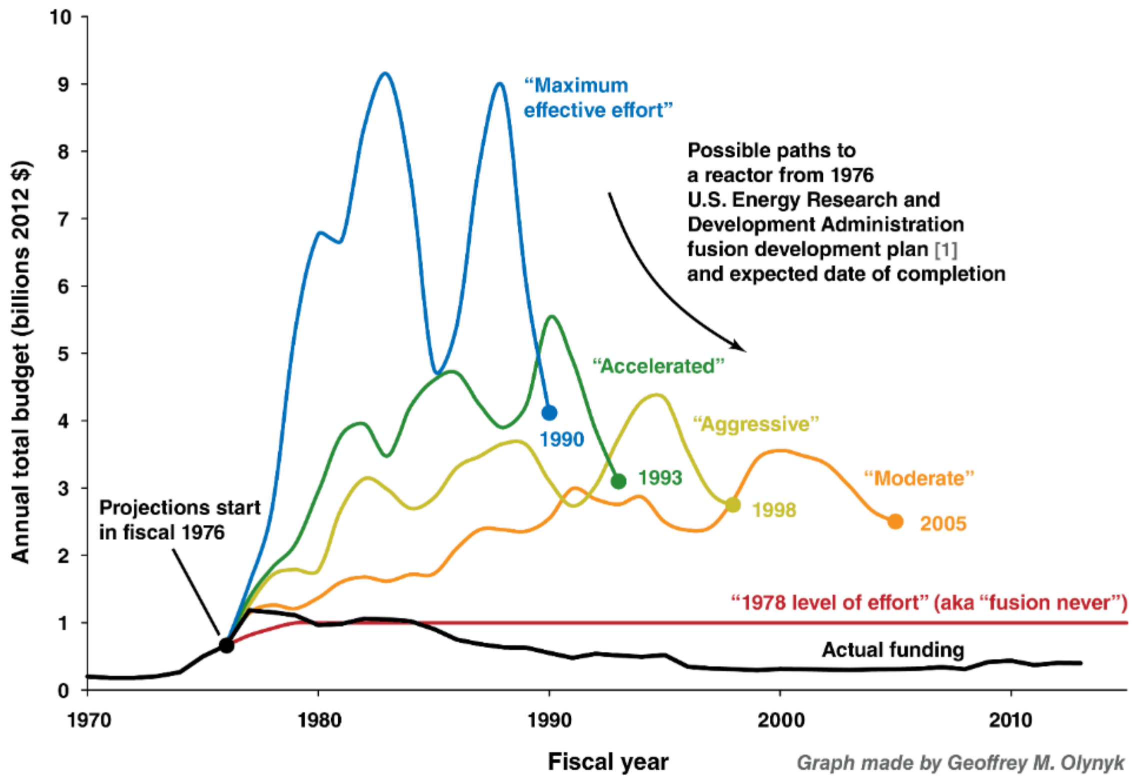
What could our world do with clean, abundant, and reliable fusion energy? Almost anything one can dream of, and likely a great number of things we have yet to imagine. In addition to the aforementioned improved living standards, there is great potential for producing synthetic fuels (e.g., diesel and jet fuel) without having to pull oil and gas out of the ground. Other possible uses include the production of green hydrogen, desalination to provide needed fresh water to dry coastal areas—even making deserts bloom if we so desire, and helping decarbonize steel and cement production. It could also greatly speed up our expansion into space, helping us unlock the riches of the Solar System far sooner than would otherwise be possible.

Why do we not have fusion yet?

Unfortunately, nothing is perfect, and fusion is no exception. You may have heard that fusion is perpetually 30 years away; and in the past, there has been a lot of truth to that accusation. The biggest downside is also the most obvious: nobody has made it work practically yet. There has been tremendous progress, but attaining energy breakeven, where the energy produced by the reaction is equal to the energy expended in making it occur, was only reached (and surpassed) very recently. In December 2022 the National Ignition Facility (NIF) announced that they had successfully achieved net energy gain, where the fusion fuel produced more energy than the lasers igniting it supplied.[31] A stupendous breakthrough, but nowhere near what is needed for commercial power generation. Overall, fusion was harder than expected, and some of the technology needed to make it work in a practical way simply hadn't been invented until more recently. Better plasma simulations (requiring fairly modern computers to run them), more efficient lasers, and high temperature superconducting magnets are examples of this.

As mentioned before, one of the most commonly planned fusion fuels is Deuterium–Tritium. The biggest difficulty with D-T is that around 80 percent of the reaction's energy is in the form of high energy neutrons. These have the unfortunate effect of slowly turning materials they interact with radioactive, necessitating replacing parts every few years, as well as requiring shielding around the reactor core. Thankfully though, the radioactivity from tritium and from the effects of high energy neutrons is relatively weak, requiring only decades of storage, as opposed to centuries or millennia for traditional nuclear waste. The best analogy is to medical waste, or the radioactive byproducts produced during the operation of particle accelerators, neither of which constitute serious problems, and for which good waste management solutions exist.

[31] "National Ignition Facility achieves fusion ignition." Lawrence Livermore National Laboratory. Dec 14, 2022. https://www.llnl.gov/news/national-ignition-facility-achieves-fusion-ignition.



[1] U.S. Energy Research and Development Administration, 1976. “Fusion power by magnetic confinement: Program plan” ERDA report ERDA-76/110. Also published as S.O. Dean (1998), *J. Fus. Energy* **17**(4), 263–287, doi:10.1023/A:1021815909065

Figure 5: Fusion funding over time in the United States.[32]

Another problem is cost. The world’s biggest fusion experiment, ITER, is way over budget and behind schedule. Final costs may be up to US$65 billion.[33] This issue is mostly specific to ITER, but unfortunately the project has taken the lion’s share of money directed at fusion for the past couple decades. The last big concern has been the chronic lack of funding. As you can see from Figure 5, funding to develop fusion in the United States pretty much stayed below the estimated “fusion never” line. This has changed, particularly in the last few years. Yet overall levels of government funding are still low, especially when compared to R&D funding for renewables. Basically, if we had invested the money, we could have reasonably expected to have had fusion 30 years ago in the early 1990s, based solely on American efforts.

Progress is happening though, with NIF achieving both breakeven and net energy gain for the first time, and multiple private companies planning to do the same by the end of this decade. The ultimate goal is to achieve a high energy gain, where the reaction generates *significantly* more energy than it consumes. Energy gain is generally denoted as Q. When Q reaches 1, it means that the energy produced equals that

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[32] “Fusion power by magnetic confinement: Program plan.” U.S. Energy Research and Development Administration. 1976. ERDA report ERDA-76/110. Also published as S.O. Dean (1998). J. Fus. Energy 17(4), 263-287. Doi:10.1023/A:1021815909065.

[33] “ITER disputes DOE’s cost estimate of fusion project.” Physics Today. April 16, 2018. https://physicstoday.scitation.org/do/10.1063/PT.6.2.20180416a/full/.

of the energy heating the fusion fuel. Practically however, this isn't enough to self heat the fuel, because not all of the energy produced can be captured. Self heating may require a Q value of about 5.

There are different types of breakeven. First is what's often called *scientific breakeven*, which is what NIF achieved when its lasers input 2.05 megajoules (MJ) of energy to the target, resulting in 3.15 MJ of fusion energy output. It's about producing as much (or more) energy from the fusion reaction than the energy used to drive it. This is just considering the energy in the plasma, and ignoring all the other power requirements (e.g., running the machine). Next is *engineering breakeven*, where you're producing enough electricity to actually run your machine, not just heat the plasma or compress the target. The ultimate goal is *economic breakeven*, which is what you need in order to make commercial fusion power plants a reality, and involves producing enough surplus electricity or heat to sell.

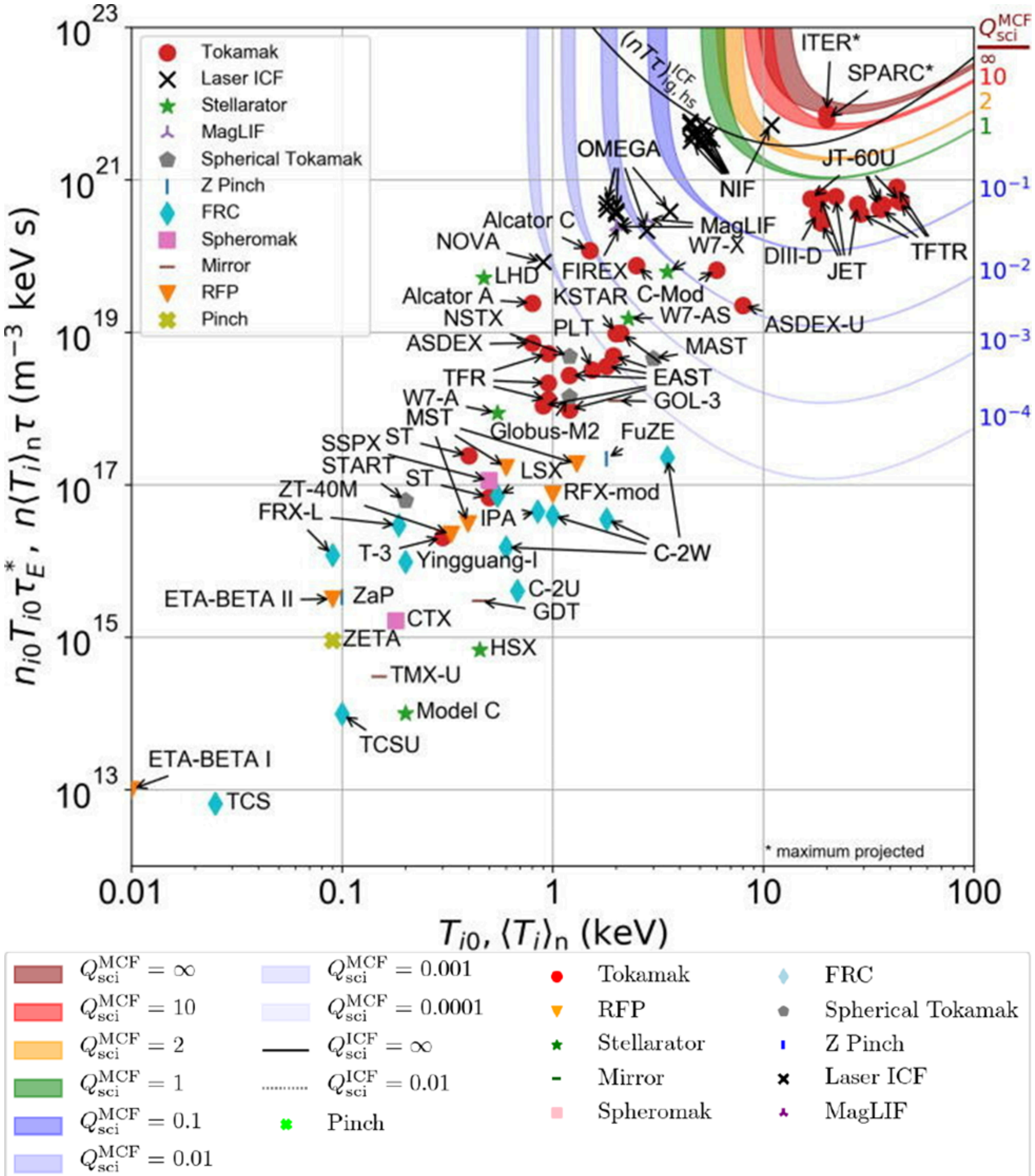

Figure 6: Progress Towards Fusion Energy Breakeven and Gain as Measured Against the Lawson Criterion[34] Colored contours are for scientific Q relevant to MCF (e.g., tokamaks). The black curve represents the hot-spot ignition condition for laser ICF.

Figure 6 above shows the actual and projected scientific Q-values of various fusion projects, including ITER and a machine called SPARC, being built by a private company. Both will be just shy of what's needed for true commercial operations. If every private fusion company dedicated resources towards publishing peer reviewed data on their reactor capabilities, it is possible there would be more proposed

[34] Wurzel, Samuel E., and Hsu, Scott C. Progress toward fusion energy breakeven and gain as measured against the Lawson criterion. 2022. Physics of Plasmas 29, 062103. https://doi.org/10.1063/5.0083990.

machines from private companies clustering around or beyond SPARC and ITER. A time scale isn't shown, but the trend has been towards higher Q-values in the upper right corner. Q-values are determined by looking at the Lawson Criteria. It consists of three terms: Plasma (fuel) density, energy confinement time, and temperature. Together, they are commonly used to gauge fusion's progress towards energy breakeven and beyond.

The Current Landscape of Fusion Development

Government

The most significant progress has been the National Ignition Facility in the United States reaching ignition in 2022,[35] and, as mentioned earlier, having recently achieved the further milestone of net energy gain. It doesn't count all the energy needed to power the lasers, and NIF wasn't designed as a power plant—nonetheless, it's a big step in the right direction.

Elsewhere, the world's largest fusion project, ITER[36], is a tokamak being built in the south of France, breaking ground in 2007. It's designed to provide a testbed for fusion technology, and eventually produce a net energy gain of 500 MW (thermal) from a 50 MW electrical input. ITER won't actually produce electricity, but is intended to serve as a precursor for an even larger tokamak called DEMO.[37] This in turn will show fusion is capable of producing electricity, helping inspire the design of more efficient and economical power plants. All of that sounds great, until you look at the cost overruns and timeline. Currently under construction, ITER won't start plasma tests until at least 2027, or D-T fusion before 2036-37. DEMO operations are currently slated to begin in the mid-2050s.

Several governments aren't interested in waiting another 30+ years for DEMO to prove itself, and have started their own programs with accelerated timelines. In 2020 the Department of Energy in the United States published a report calling for public and private investment in an American built fusion power plant, with a goal of starting to provide electricity to the grid by 2040[38]. Around the same time, a bipartisan fusion caucus was formed. More recently, the annual budget for fusion research was increased, and $50 million dollars in new funding for advancing fusion was announced.[39] In November 2022, the U.S. Government made an extremely significant announcement—naming the commercialization of fusion as one of their top five priorities to help enable the country to meet its goal of net-zero emissions by 2050.[40] In the U.K., the government has set aside several hundred million pounds for their fusion program, with a goal of electricity production by 2040.[41] Nor are western

[35] "Achieving Fusion Ignition." LLNL. https://lasers.llnl.gov/science/pursuit-of-ignition
[36] "What Is ITER?" ITER. https://www.iter.org/proj/inafewlines.
[37] "The demonstration power plant: DEMO." EUROfusion. https://www.euro-fusion.org/programme/demo/.
[38] "Powering the Future Fusion & Plasmas." Fusion Energy Sciences Advisory Committee. 2020. https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/FESAC_Report_2020_Powering_the_Future.pdf.
[39] "Department of Energy Announces $50 million in Funding for New Public-Private Partnerships." Fusion Industry Association. Sept 23, 2022. https://www.fusionindustryassociation.org/post/department-of-energy-announces-50-million-in-funding-for-new-public-private-partnerships.
[40] U.S. Innovation To Meet 2050 Climate Goals. The White House. November, 2022. https://www.whitehouse.gov/wp-content/uploads/2022/11/U.S.-Innovation-to-Meet-2050-Climate-Goals.pdf.
[41] "UK invests in domestic fusion plant." World Nuclear News. Oct 3, 2019. https://www.world-nuclear-news.org/Articles/UK-invests-in-development-of-domestic-fusion-plant.

governments the only ones pursuing fusion. China is designing its own tokamak, which has two phases that parallel ITER and DEMO, but with a faster timeline.[42] Plans aim for completion in the 2030s and 2040s respectively. Japan has recently launched ambitious fusion plans as well.[43]

Private Companies / Sector

There has been a lot of encouraging progress in the private sector in recent years, including an explosion in the number of private fusion companies, and in the variety of their approaches. There are at the moment over 50 companies that together have attracted over US$6 billion in mostly private investments.[44] Much of this funding has been in the last few years, marking a huge increase over the almost non-existent money a decade ago, yet still a paltry sum compared to expenditures for renewables or ITER. There's now even a Fusion Industry Association[45], founded in 2018, to help the nascent fusion industry speak with amplified voice, and to begin working with governments on regulations suitable for fusion energy.

At the moment, it's difficult to pick which companies are leading the pack, or have the best reactor concepts and designs. Some of the larger companies that have managed to raise the most money include TAE Technologies, Helion Energy, Commonwealth Fusion Systems, and Zap Energy in the U.S., Tokamak Energy in the U.K., and General Fusion in Canada. Most of these large companies believe they will achieve their energy break-even moment this decade, and aim to have commercial prototypes providing electricity by 2030, or shortly thereafter. But money raised does not necessarily mean best concepts, and there are numerous promising smaller fusion players in various stages of development as well.

Fusion Energy: The Solution to Our Energy Problems

As mentioned before, fusion compares very favorably to other energy sources on externalities. Fusion will be reliable, able to operate 24/7; and it won't depend on location or require geopolitically restricted resources such as oil or uranium. Fusion is the solution to our energy problems, and we believe that hyperfusionization is the best possible way to power the future of human civilization. Our belief is that abundant and reliable energy is the base upon which almost everything else good and worthwhile is built. Fusion will help provide energy for a world needing 50% more of it by 2050, and address climate change in a framework that prioritizes energy abundance, reliability, and security.[46]

Fusion Energy as an Investment Case

Competent investment managers understand that a business which provides a valuable product or service may not always be a suitable investment. Investment managers need to assess a variety of risks and weigh those against potential rewards. All investments in early-stage companies focused on fusion

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[42] "China's fusion roadmap." Nuclear Engineering International. Oct 3, 2019, Yuntao Song. https://www.neimagazine.com/features/featurechina-fusion-roadmap-7436879/.
[43] "Japan to draft nuclear fusion strategy amid fierce global race." The Asahi Shimbun. Sept 14, 2022, Yu Fujinami. https://www.asahi.com/ajw/articles/14718757.
[44] "The global fusion industry in 2023." Fusion Industry Association. https://www.fusionindustryassociation.org/wp-content/uploads/2023/07/FIA%E2%80%932023-FINAL.pdf.
[45] Fusion Industry Association. https://www.fusionindustryassociation.org/.
[46] "INTERNATIONAL ENERGY OUTLOOK 2021." EIA. Oct 6, 2021. https://www.eia.gov/outlooks/ieo/consumption/sub-topic-03.php.

research and development come with significant risks including scientific uncertainty and unproven commercial viability.

We feel that the best approach to investing in fusion energy is through a model which accounts for the expected value of risk-adjusted returns.

We identified 3 mental models to analyze fusion energy through the investment lens.

1) Fusion is a **disruptive competitor** that can outcompete legacy technologies in energy markets.
2) Fusion is a **breakthrough energy innovation**, akin to the steam engine or electricity.
3) Fusion is a **significantly subsidized industry** with potential non-fusion adjacent revenue sources.

Disruptive Competition

Perhaps the most simplistic approach to evaluating investments in fusion energy is to look at the consensus around the future cost competitiveness of fusion energy and analyze the potential market share that can be taken from legacy energy sources. The global energy market serves an extremely diverse group of customers primarily divided into two categories:

> On-grid: Residential/commercial/industrial power supply, battery chargers, etc.
> Off-grid: Combustion engines in automobiles/ships/aircraft, remote industrial systems, etc.

We believe that fusion energy will be most competitive in levelized cost of energy for on-grid users. Early commercial fusion energy is likely going to require large scale deployments to gain economies of scale. Although there are some ongoing efforts to develop small, modular, or transportable fusion energy reactors, we believe, based on the totality of evidence, that these small designs are less likely to be the first to commercial market. Large fusion reactors will likely serve the biggest energy consumers first – massive grid energy especially for concentrated areas of industrial activity.

Data from the Department of Energy bracket the range of costs associated with various forms of grid power generation. The levelized cost of energy (LCOE) varies greatly by region, plant operator, and fuel source, but the average plant produces energy at an LCOE of $40/MW[47]. While no fusion plants have been commercially deployed to date, it is possible to project the capital costs of building a plant based on the costs of experimental reactors, and it is also possible to project the approximate LCOE of a fusion plant based on a combination of scientific and experimental data. Recent estimates suggest that the average fusion plant may have a LCOE as low as $34/MW[48]. These cost projections validate the thesis that fusion is cost-competitive and potentially a cheaper source of energy than legacy fuels, while also offering environmental, sustainability, and total capacity advantages.

[47] "Levelized Costs of New Generation Resources in the Annual Energy Outlook 2022." EIA. March 2022. https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

[48] "Revisit of the 2017 Costing for Four ARPA-E ALPHA Concepts." Woodruff Scientific. October 19, 2022. https://arpa-e.energy.gov/sites/default/files/2021-03/Final%20Scientific-Technical%20Report_%20Costing%20%286%29.pdf.

The US Government estimates that domestic on-grid demand is 4 trillion kilowatt hours per year[49] with natural gas as the fastest-growing category of power plant largely driven by displacement of coal plants.

Breakthrough Innovation

As a breakthrough energy innovation, fusion energy may have similar returns as historical energy breakthroughs such as the steam engine or electricity. Commercial fusion has the potential to deliver high-capacity grid power, 24/7, with little or no environmental impact. These features, unique to fusion among all extant energy sources, have the potential to dramatically improve life on a global scale. The geopolitical strife associated with natural energy resources would effectively become unimportant, overnight. The world's governments would be compelled by their constituencies to compete on delivering more fusion energy capacity for the populace. We believe that fusion energy as an infrastructure will be on par with the innovations of public sanitation, radio communications, electricity, and the internet. While the engineering challenges of achieving commercial fusion energy are extraordinary, and the financial risks may also be extraordinary, we believe the rewards offer a unique asymmetric return profile not often accessible to investors.

We believe that the combined total market capitalization of all private fusion energy companies today is under $50B. Some estimates have projected fusion maturing into a $40T[50] industry, implying a 80,000% growth from the valuation of all fusion energy companies' combined mark-to-market valuations in 2022.

Subsidized Industry

It is important for investors to consider the significant government subsidies that will offset fusion energy research, development, and commercialization costs. There are several different subsidies which fusion energy companies already take advantage of today, and will likely take advantage of in the future.

1) **Department of Energy:** The US DOE provides grants annually to a wide variety of fusion energy companies. In 2022 the total DOE grant pool was $50M, divided among several companies. "These funding opportunities support foundational science and technology research connected to high-priority issues for a future fusion pilot plant, including plasma modeling, interactions, and control."[51] – Geraldine Richmond, DOE Under Secretary for Science and Innovation.
2) **Advanced Research Projects Agency – Energy (ARPA-E):** ARPA-E facilitates cooperative cost sharing for fusion energy projects, which allows for public subsidies between *80-90%*[52] of the total project cost, with 10-20% contributed by private capital.
    a. *2016: Accelerating Low-Cost Plasma Heating (ALPHA[53] Program)* – 9 fusion energy projects funded for $30M in grants. Some program participants have seen tremendous

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[49] "U.S. Electricity Grid and Markets." EPA. May 5, 2022. https://www.epa.gov/green-power-markets/us-electricity-grid-markets.
[50] "Nuclear fusion market could achieve a $40 trillion valuation." Bloomberg Intelligence. https://www.bloomberg.com/professional/blog/nuclear-fusion-market-could-achieve-a-40-trillion-valuation/
[51] "Department of Energy Announces $50 Million for Fusion Research at Tokamak and Spherical Tokamak Facilities." U.S. Office of Science. March 17, 2022. https://www.energy.gov/science/articles/department-energy-announces-50-million-fusion-research-tokamak-and-spherical.
[52] "General Questions." ARPA-E. https://arpa-e.energy.gov/faqs/general-questions.
[53] "ALPHA." ARPA-E. https://arpa-e.energy.gov/technologies/programs/alpha.

success after their ARPA-E partnership concluded. For example Helion Energy[54] has seen its valuation increase from $15M 2015 to $3B[55] valuation in 2022 after its most recent $2.2B Series E raise, providing up to 20,000%+ return on equity for their seed round investors after 7 years.

b. *2018: OPEN 2018*[56] – 45 breakthrough energy projects funded for a total of over $112M in federal funding including notable fusion projects such as CTFusion, Princeton Fusion Systems, and Zap Energy.

c. *2019: Breakthroughs Enabling THermonuclear-fusion Energy (BETHE*[57] *Program)* – 15 fusion projects took $32M in grants. Some BETHE program participants have achieved significant success since completing their ARPA-E programs including Zap Energy (now valued at $1B+[58]) and Commonwealth Fusion Systems (now valued at $1.6B[59]).

d. *2021: Galvanizing Advances in Market-Aligned Fusion for an Overabundance of Watts (GAMOW*[60] *Program)* – 14 fusion energy projects funded for $29 million in grants including Princeton Fusion Systems and Bridge 12 Technologies.
Note: ARPA-E is not directly responsible for the increase in valuation of any fusion company participating in its programs, however the program participants we highlighted above have achieved significant financial milestones independently of ARPA-E.

3) **Carbon Offset Credits:** Because a commercial fusion energy production plant would produce no carbon emissions, we hypothesize that fusion energy companies could be eligible in the future for the largest ever carbon offset credits. As of 2021 the average global market price of a carbon credit was priced at $\$3.82/tCO_2e$[61]. In 2020 the US energy grid was estimated to produce 4.01 trillion kWh with a byproduct of 1.55 billion metric tons of CO_2. Under our hyperfusionization theory under which 90%+ of future grid energy is produced by commercial fusion energy sources, we estimate that **fusion energy industry in its totality could qualify for up to $5.4 billion in carbon offset subsidies from the US grid alone**, not accounting for global carbon reduction incentives which may be far more substantial than US incentives.

Given (1) the economics of disruptive market competition, (2) the market opportunity for breakthrough energy innovation, and (3) the tailwinds of a blended subsidy, we believe that fusion energy should be viewed as a heavily subsidized opportunity to invest in breakthrough energy innovation with an asymmetric return potential.

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54 Helion. https://www.helionenergy.com/.
55 "Fusion energy startup Helion raises $500 million" Axios. Dan Primack, Nov 5, 2021. https://www.axios.com/2021/11/05/helion-500-million-funding-sam-altman.
56 "OPEN 2018." ARPA-E. https://arpa-e.energy.gov/technologies/programs/open-2018.
57 "BETHE." ARPA-E. https://arpa-e.energy.gov/technologies/programs/bethe.
58 "Zap Energy nets $160M Series C to advance its lightning-in-a-bottle fusion tech." Tech Crunch. Tim De Chant, June 22, 2022. https://techcrunch.com/2022/06/22/zap-energy-nets-160m-series-c-to-advance-its-lightning-in-a-bottle-fusion-tech/.
59 "Commonwealth Fusion Systems Raises $1.8 Billion in Funding to Commercialize Fusion Energy." Commonwealth Fusion Systems. Dec 1, 2021. https://cfs.energy/news-and-media/commonwealth-fusion-systems-closes-1-8-billion-series-b-round.
60 "GAMOW." ARPA-E. https://arpa-e.energy.gov/technologies/programs/gamow.
61 "What influences carbon offset pricing?" Climate Trade. https://climatetrade.com/what-influences-carbon-offset-pricing/.

Conclusion

The potential we see for hyperfusionization is to create a new paradigm, both in how we power our world and in how we invest for the future. We believe that once commercialized, fusion will usher in an era not just of energy security and reliability, but of energy abundance.

As an investable industry, fusion is a hedge against disruptive competition in today's energy markets. Hyperfusionization may also represent a generational wealth generating opportunity. Every institutional investor considering capital allocations in energy or disruptive technologies should give critical thought to what role fusion plays in a portfolio – is 0% fusion really an appropriate allocation? Most fusion companies are pre-revenue, although some fusion companies have revenue opportunities through adjacent or enabling technologies, and all fusion companies we evaluated are eligible for or have received government subsidies to offset cash burn.

Looking at history, we see that adoption of new energy sources with higher energy density improves standards of living, and increases prosperity and abundance. These transitions from lower to higher energy density fuels have happened several times, and generally occur naturally unless political interference transpires. Fusion is the most energy dense source of power we know of, making it the inevitable culmination of the path that started with fire kindled in wood, and now ends with the fire kindled in the hearts of stars.